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# Unbundling in Optical Access Networks: Focus on Hybrid Fiber-VDSL and TWDM-PON

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**Abstract**—The paper presents an overview of unbundling techniques for Next Generation Access Networks. In particular, the advantages and drawbacks of unbundling solutions for hybrid fiber-copper and all-optical access networks are discussed and compared.

**Keywords**—optical access networks, unbundling, VDSL2-vectoring.

## I. Introduction

Unbundling the local loop (ULL), or unbundling for short, is a set of regulatory and technical solutions for providing emerging operators (namely Other Licensed Operators – OLOs) access to last mile communications networks already deployed by incumbent operators, indicated as “incumbent local exchange carrier” (ILEC) in this paper. In the idea of the regulators, ULL shall ease access to the market by new operators, thus increasing competition and decreasing prices for the end users.

On the regulatory side, in view of the persistent difficulties in the European Union (EU) to effectively promote the development of Next Generation Access networks (NGAN) based on private investments, the EU Commission recently published a Recommendation [1] aiming at encouraging investments in new networks. The Recommendation establishes that the wholesale ULL prices fixed for the old copper networks (i.e., Digital Subscriber Line, DSL) should at least not decrease, while for the new optical networks (or hybrid networks) the cost-orientation obligation on tariffs can be removed.

In parallel, the EU has also clearly set the final goal of NGAN through the 2011 EU official document titled “Digital Agenda for Europe”, which mandates that by 2020 not less than 50 percent of European households should be able to subscribe contracts at speeds over 100 Mbit/s. This goal is clearly not feasible with current pure-copper access networks, and thus requires the deployment of NGAN, which partially or totally replace copper with fibers. The issue of deploying NGAN and at the same time ensuring unbundling options is thus becoming a key topic, at least in the European telecom market.

Technical solutions for implementing NGAN can be classified in two main classes: one class is the one where fiber is utilized to carry data until some access network substation

and xDSL is utilized for reaching the end user; in the other class, the fiber directly reaches the end user. Solutions belonging to the former class are generally addressed as *hybrid solutions* while solutions belonging to the second class are known as *all-optical solutions*. Hybrid solutions include Fiber to the Cabinet (FTTCab), Fiber to the Curb (FTTC), Fiber to the Distribution Point (FTTDp) and Fiber to the Building (FTTB). Fiber to the Home (FTTH) is the only all-optical solution, so far.

In traditional twisted-pair copper access networks, unbundling is based on two main strategies:

- “physical layer” ULL, implemented by moving twisted pair cables inside the central office (CO) from the ILEC Digital Subscriber Line Access Multiplexer (DSLAM) to the OLO DSLAM;
- “network layer” solutions, based on switching the data traffic at upper network layers (commonly at the data link layer), either remotely (a technique usually called “bitstream”) or locally inside the CO (virtual unbundling of the local loop, or VULA<sup>1</sup>).

Similar techniques can be implemented also in NGAN. However, they might present different advantages and drawbacks, depending on the specific NGAN architecture considered. Physical layer solutions for unbundling NGAN present many hurdles currently. In case of hybrid solutions, the two main hurdles are represented by the architecture of the Passive Optical Network (PON), which can be utilized to reach the cabinet, and by the utilization of vectoring on the xDSL side to reach the end user. The former hurdle is represented by the PON tree, which has only one fiber entering the CO over which point-to-multipoint transmission is achieved by a highly centralized Time Division Multiple Access (TDMA) organization. Consequently, it is impossible to directly replicate the “physical layer” ULL adopted for copper access networks. The latter hurdle is represented by the fact that, to provide high speed (for instance to meet the EU 100 Mbit/s per user goal) vectoring techniques should be implemented on the copper links, but in turns vectoring requires a heavy coordination between transmissions along

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<sup>1</sup> VULA (Virtual Unbundling of the Local Access) is a layer 2 wholesale access product originally introduced by OFCOM, the UK national regulator.

different twisted pairs. Such coordination is very difficult to be achieved in case of physical unbundling of the twisted pairs. Hurdles related to the TDMA PON architectures are also valid for all-optical solutions, such as FTTH.

On the other hand, network layer solutions for unbundling are highly independent from the underlying physical structure, so that both bitstream and VULA can be implemented also on hybrid and all-optical NGAN. Therefore, they appear the most straightforward and short term solution for NGAN unbundling.

However, both hybrid and all-optical access solutions are continuously evolving. For example, the newly approved Time and Wavelength Division Multiplexed (TWDM) PON standard [2] features the utilization of Wavelength Division Multiplexing (WDM) to improve PON capacity. Moreover, the G.fast standard is capable of providing aggregated US+DS data rates in the order of 1 Gbit/s in FTTP architectures. Such evolution could potentially move the current equilibrium point [3] between advantages and drawbacks for unbundling solutions. Completely new PON multiplexing architectures are also proposed by the research community, such as electrical frequency-division multiplexing (FDMA) over each wavelength [4], a solution that could also greatly support physical unbundling [5].

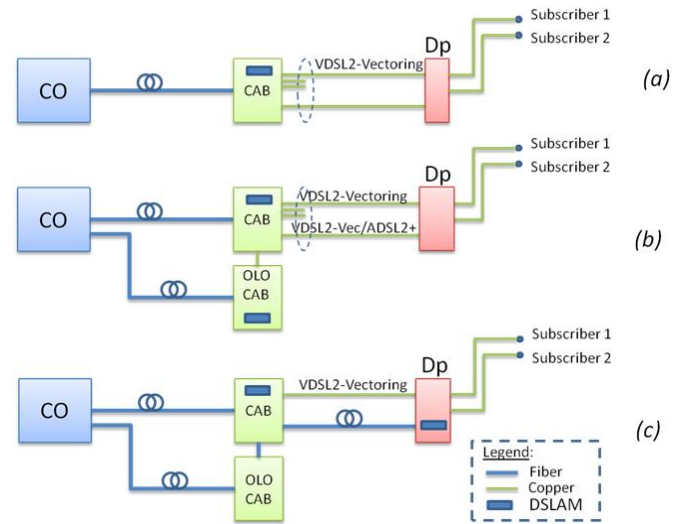
By looking at the future, this paper aims at evaluating advantages and drawbacks of physical unbundling solutions for a subset of hybrid and all-optical NGAN. In particular, FTTCab, FTTP and FTTH based on TWDM PON architectures are considered.

## II. Unbundling for hybrid Fiber-VDSL solutions

It is today envisaged to have a gradual evolution toward pure FTTH deployment by going through intermediate steps for two main reasons: *i.* the ILECs need for more flexible architectures to make network deployment costs more affordable and to reduce the implementation risks; *ii.* OLOs need for their newly developed access networks to compete with ILEC in each single geographical area. Thus, several hybrid architectures could coexist in the near future, some of them reported in Figure 1.

The copper substitution started with laying down the fiber in the primary network, i.e. from the Central Office to a street Cabinet (CO-to-CAB), and still saving the existing copper lines in the secondary network, i.e. from the street Cabinet to a Distribution point (CAB-to-Dp) and then to the final user. In Figure 1, some possible coexistence scenarios are reported when more operators offer products on the same last mile. In particular, in Figure 1 (a), only the ILEC is present and provides services to all users. In this case, one single CAB is fed by fiber from the CO, and a VDSL2 DSLAM placed in the CAB can implement vectoring for all lines with no limitations. Vectoring allows to ideally eliminate the crosstalk interference of DSL signals [6], providing bit rates up to 100 Mbit/s and thus fulfilling the EU Digital Agenda for 2020. In this scenario, physical unbundling is practically not possible at the CO, due to the presence of a single fiber pair down to the

cabinet (unless the fiber itself is duplicated). Therefore, VULA can be used to surrogate ULL [5]. In Figure 1 (b), we show a multi-carrier situation, where an OLO interfaces the incumbent's network in a physical access point closer to its customers, requesting the incumbent to provide the OLO a modality that is usually indicated as Sub-Loop Unbundling (SLU). In SLU, a DSLAM of an OLO can be housed in a small proprietary cabinet being built nearby the incumbent's existing cabinet. In this architecture, ADSL, VDSL and VDSL-vectoring of OLO and incumbent signals simultaneously appear on the very last part of the network, inside the same bundle of twisted pair. It can be shown that, in this situation, the vectoring does not produce its benefit, since the crosstalk caused by un-vectorized lines or lines related to other vectored groups within the same cable or binder, result in marked performance degradation [7]. In Figure 1 (c), we show a third possible situation, where the OLO deploys its fiber to the Dp in order to access the incumbent's network physically even closer to its customers, and then enabling it to provide services with more revenues (e.g., IPTV). The last case is of our interest considering the importance in economic and technological terms.



**Figure 1: Coexistence scenarios: (a) only one operator offering VULA service; (b) addition of one OLO cabinet to offer different FTTC products; (c) addition of one OLO cabinet to offer FTTP product.**

The performance analysis of the access system in Figure 1 (c) requires the study of signals' mutual interferences. In the following Equations (1) and (2), the signal-to-interference plus noise ratio (SINR) at the  $k$ -th sub-carrier at frequency  $f_k$  for the Discrete Multi-Tone (DMT) signal of the (generic)  $i$ -th user are reported in two cases: *i.* SINR for the user at the Cabinet  $\rho_{k,i}^C$  and *ii.* SINR for the user at the Distribution point  $\rho_{k,i}^D$ , respectively:

$$\rho_{k,i}^C = \frac{P_{k,i}^C}{N(f_k) + \sum_j T_{k,j}^D} \rho_{k,i}^C = \frac{P_{k,i}^C}{N(f_k) + \sum_j T_{k,j}^{D2C}} \rho_{k,i}^C = \frac{P_{k,i}^C}{N(f_k) + \sum_j T_{k,j}^D} \quad (1)$$

$$\rho_{k,i}^D = \frac{P_{k,i}^D}{N(f_k) + \sum_j T_{k,j}^{C2D} + \sum_{j \neq i} T_{k,j}^D} \quad (2)$$

where  $N(f)$  is the power spectral density accounting for the overall background noise,  $P_{k,i}^C$  ( $P_{k,i}^D$ ) is the received power on the subcarrier at frequency  $f_k$  of  $i$ -th CAB (Dp) user;  $\sum_j T_{k,j}^{C2D}$  ( $\sum_j T_{k,j}^{D2C}$ ) is the interference due to Far-End crosstalk (FEXT) due to other CAB (Dp) users. The expressions of the interference terms in (1) and (2) are provided in [8] and for brevity they are not reported. Note that in (1) only the interference due to Dp signals is present. In fact, CAB users are assumed to be vectored at the CAB and interference caused by other CAB users is practically null. Instead, the term  $\sum_{j \neq i} T_{k,j}^D$  in (2) is the interference due to other non-vectored Dp signals (called “self-FEXT”). All interference terms depend on the Tx-Rx distances, on the coupling lengths with the reference user and on the crosstalk transfer function for the considered  $f_k$ .

Simulation results are reported in Fig. 2. In particular, the available bit rates are reported as a function of the distance between the CAB and the Dp,  $d_{CAB-Dp}$ . No practical bit load limitation is considered in the results. The incumbent’s subscribers experience lower bit rates than OLO’s ones due to their greater distance from their DSLAM. Moreover, their bit rates decrease with the increase of  $d_{CAB-Dp}$ . On the contrary, OLO subscribers’ bit rate increases for higher  $d_{CAB-Dp}$  because the measured interference decreases as the incumbents’ users move away (circles in Dp users curves). This increase is cleared by increasing the number of interferers (squares in Dp users curves). In Fig. 2, several combinations of interference cases are considered. The degradation passing from one Dp user–rest CAB users to 50% Dp–CAB users as well as increasing the total served users (from 16 to 24) is more pronounced for Dp, since CAB users are vectored. Other spectral management techniques can be implemented to mitigate the interference between different coexisting DSL systems (e.g., Downstream Power Back Off [8,9]).

To further increase the bit-rate in the hybrid scenario, other solutions are today considered, such as different access network architectures able to reduce the length of the copper wire, including FTTP, where the “Dp” is located close to the building or inside it. In this context, several scenarios can coexist simultaneously as FTTC and FTTP before the FTTH making ULL practically not feasible. In addition to VULA, it is possible to implement SLU but performance degradation even with vectored signals should be carefully evaluated in operator fiber deployment strategies.

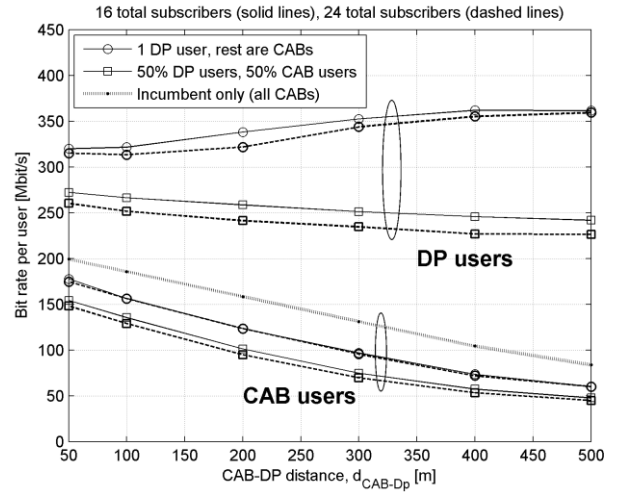
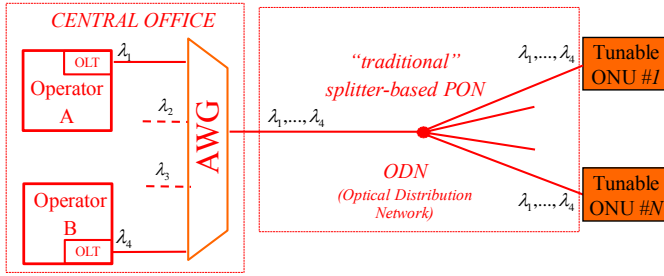


Figure 2: 50-th percentile bit rate per users vs CAB-Dp distance for subscriber served at CAB and at Dp.

### III. Unbundling in NG-PON2 ITU-T G.989.1 TWDM-PON

In order to find a proper balance between increased capacity and cost, ITU-T recently released (end of 2013) its most advanced standard for PON in Recommendation G.989, which is today usually indicated as NG-PON2 or, more specifically, as TWDM-PON. In this new standard, four wavelengths are used per direction over a “traditional” PON architecture, i.e. an optical tree using passive optical splitter. To obtain maximum backward compatibility, TDMA is still used over each wavelength. In this architecture, each ONU is equipped with optically tunable transmitters and receivers, to be able to work on any of the four wavelengths, which are placed on a 100 GHz frequency grid. ITU-T main goal when defining the G.989 TWDM-PON standard was a four-fold increase in capacity compared to G.987 XG-PON. Anyway, as shown in Fig. 3, TWDM-PON is also interesting to perform physical layer unbundling up to four operators, each one using a dedicated wavelength that simultaneously reaches its own group of ONUs, still shared in TDMA as in “traditional” PON standards. In this scenario, each of the four possible operators will thus handle an XG-PON, which is in principle independent on the other XG-PON managed by the other operators. Consequently, a user subscribing to a specific operator will tune its ONU transceivers to the operator specific wavelength pair (one wavelength per direction).

Using this WDM approach, it will be possible to implement true physical layer unbundling over PON, while this was impossible in previous PON standards (such as BPON, GPON and XGPON), a solution that has also been shown to be economically interesting compared to others [3].



**Figure 3: Unbundling architecture in TWDM-PON (downstream only)**

The remaining problems to be solved are mostly in the coordination of the upstream wavelengths. This is not yet defined in the standard, but in order to keep the ONUs cost low, very likely the ONUs will not be required to have an “absolute” accuracy on their output upstream wavelengths (as it is done today in tunable lasers for long-haul optical applications). A centralized control of the upstream wavelengths will probably be implemented from the CO side. In a nutshell, a CO “wavelength control entity” will remotely drive the ONUs upstream wavelengths in the proper position on the WDM grid. In an unbundling scenario such as the one shown in Fig. 3, this “entity” will be the only function requiring some coordination among the different operator ONUs, thus adding some complexity in the unbundling actual implementation.

#### iv. Conclusions

We have discussed in this paper several options for unbundling in NGAN, showing the network layer solutions currently implemented on traditional copper-based networks (bitstream and VULA) can be directly applied also to NGAN. The situation is completely different for physical layer unbundling, which appears to be very critical on NGAN, and in fact:

- for the hybrid fiber/VDSL solutions, the fiber segment necessarily needs to be duplicated for a fair access among several operators. For what concern the copper part, the situation is really critical if vectoring is used, but vectoring is a must to reach the 100 Mbit/s target. This is thus a completely open technical issue for the moment;

- for the all-optical FTTH case, unbundling is trivial for optical point-to-point architectures (not discussed in this paper) but very critical for PON architectures. On PON, the only viable solution for physical unbundling seems to be adopting the WDM “degree of freedom”. The last ITU-T Recommendation for PON [2] has introduced WDM in PON for the first time. Even though the ITU-T decision was mostly driven by obtaining an increase in overall capacity, it can also lead to an interesting unbundling solution.

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